January 1963

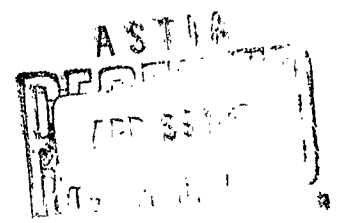SUBMILLIMETER WAVE COMPONENT DEVELOPMENT

by

O. F. Hinckelmann, H. J. Hindin, and J. J. Taub

AIRBORNE INSTRUMENTS LABORATORY
A DIVISION OF CUTLER-HAMMER, INC.

Deer Park, Long Island, New York

REPORT NO. 2098-I-2

Contract AF 30(602)-2758

Prepared for

ROME AIR DEVELOPMENT CENTER
RESEARCH AND TECHNOLOGY DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
GRIFFISS AIR FORCE BASE, NEW YORK

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PUBLICATION REVIEW

This report has been reviewed and is approved.

Approved: ARTHUR J. FROHLICH
Chief, Techniques Laboratory
Directorate of Aerospace Surveillance & Control

Approved: WILLIAM T. POPE
Acting Director
Director of Aerospace
Surveillance & Control

ABSTRACT

Techniques for the design, construction, and evaluation of a 10-db directional coupler, a 0 to 40 db variable attenuator, a 90-degree phase shifter, and a duplexer to operate in the submillimeter region were investigated theoretically and experimentally. Oversize-waveguide quasi-optics has been chosen as the technique to be pursued on the basis of theoretical studies and data obtained in the submillimeter region. Prototypes of all of these components except the duplexer have been constructed. A generation and detection scheme has been constructed and is being evaluated for the submillimeter frequencies. Successful tests of components have been made at 125, 240, and 330 Gc.

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LIST OF ILLUSTRATIONS

PAPER DELIVERED DURING THIS QUARTER

A paper, based on the results of this program, entitled, "Submillimeter Components Using Oversize Quasi-Optical Waveguide," by J. J. Taub, O. F. Hinckelmann, H. J. Hindin, and M. L. Wright has been presented at the IRE-PGMTT Conference on Millimeter and Submillimeter Waves held at Orlando, Florida, in January 1963.

I. INTRODUCTION

This is the second quarterly report describing the design and fabrication of components for operation in the submillimeter frequency range. Oversize-waveguide quasi-optics has been the most useful of the four transmission-line techniques considered. We have fabricated or are fabricating the following units with this technique: a directional coupler, a variable attenuator, a phase shifter, and a duplexer.

Our effort in the last quarter (reference 1) was divided into four tasks:

1. Final establishment of the fact that oversize-waveguide quasi-optics is a practical technique for making components,

2. Continued fabrication of these components,

3. Testing of these components at submillimeter frequencies,

4. Development and implementation of test instrumentation for in-house testing in the submillimeter range.

Of the original techniques considered, only trough waveguide was investigated in this quarter as an alternate to oversize-waveguide quasi-optics. In the light of other work (reference 2) and experimental verification of the successful operation of oversize-waveguide components at 330 Gc, it is believed that emphasis on component development in the submillimeter region should be placed on oversize-waveguide quasi-optics--particularly in the interest of making operating components.

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II. COMPONENTS

A. GENERAL

At present, we have completed prototype versions of a variable attenuator, a directional coupler, and a phase shifter. These components may be used with matched or unmatched Rexolite or quartz prisms. A quartz multiple-slab directional coupler and a grating duplexer enclosed in over-size waveguide are now under construction. The construction and operation of each component is described in this section.

Since component construction permits testing at all frequencies greater than the standard frequency for the wave-guide used, we have been testing at various frequencies until our own submillimeter source becomes operative. In fact, our components have been tested at 125 and 240 Gc at AIL and at 330 Gc at Lincoln Laboratory.

B. DOUBLE-PRISM STRUCTURES

1. VARIABLE ATTENUATOR

Figure 1 shows the O to 40 db double-prism attenuator. This device was tested at 125 Gc to obtain some indication of its behavior as far as material losses and operating characteristics are concerned. Also, since the performance of the component is theoretically predictable at any frequency, it was a good test of the general usefulness of the principles involved.

We used the Amperex DX-237 klystron at 125 Gc. This is the same tube that is being used in the harmonic generation setup. For this frequency, the ten-times oversize waveguide (at 330 Gc) used to make the variable attenuator was only three-times oversize and there was some deterioration in the behavior of this device since our wave propagation was not completely planar. We also expected a higher waveguide loss. The two prisms were unmatched to the 125-Gc signal. Further-more, we did not expect to obtain a 40-db attenuation range because the attenuation is almost linear with d/λ (where d is the separation between prisms). Thus, for a given maximum d (caused by mechanical reasons), an increase in λ causes a decrease in d/λ and in available attenuation.

Figure 2 shows the attenuation versus prism separa-tion for the variable attenuator at 125 Gc. It also shows the theoretical curve that would result if the dielectric constant (ϵ_r) of the prisms had remained unchanged at 2.55

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(its 30-Gc value) for a 125-Gc signal. The curves are in close agreement with the maximum deviation 0.5 db. This difference is the result of the inability to obtain a true zero gap (giving us more attenuation than the micrometer reading would indicate) and the not totally planar wavefront impinging on the prisms (waveguide is only three-times oversize). Thus, instead of a 45-degree angle of incidence on the prism interface, there is a spectrum of angles clustered around 45 degrees. We also know that the prisms are mismatched causing reflections at all four air-dielectric interfaces.

Despite the inaccuracies described, the predicted performance of the double-prism device is in excellent agreement with the experimental attenuation versus spacing curve at 125 Gc. Also, these results gave us added confidence in the ability of the attenuator to function in the submillimeter region.

The first test of an oversize-waveguide quasi-optical component in the submillimeter region was performed at 330 Gc at Lincoln Laboratory using the variable attenuator described. The data obtained showed the feasibility of the device and technique at these frequencies.

The Lincoln Laboratory facility uses a CSF carcinotron with a waveguide output four-times oversize for 330 Gc so that potential mode purity problems exist. (Figure 3 is a block diagram of the measurement setup.) The variable attenuator used was not matched for a 330-Gc signal and together with the sources of error mentioned in the 125-Gc test gave the data shown in Figure 4. The results are in close agreement with the theoretical predictions and they also provide the first accurate measurement of the dielectric constant of Rexolite at 330 Gc (ϵ_r = 2.45).

The power supply for the tube was incapable of modulation and a ferrite RF modulator had to be used. Unfortunately, this device produces a 90-degree polarization and the rotated component not being sufficiently attenuated affected the performance of the coupler. Several crystals were tried as detectors but the best sensitivity was obtained with a millimeter bolometer (10 db better than the crystal). Electrical noise in the laboratory limited measurement accuracy and averaging was necessary. For this reason, all data was taken with error estimates. The dynamic range was limited to 20 db because of the problems described. Several tapers and various pieces of waveguide hardware caused mode conversion and insertion loss problems because of misalignment at the flanges.

The measured loss of the coupler was 6 db most of which can be attributed to the Rexolite loss. Mode conversion, mismatch, imperfect parallelism in the prism faces, and polarization problems account for the remainder of the loss.

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The results of the preliminary measurements on the double-prism attenuator are most encouraging and further work at 330 Gc would eliminate some of the sources of error mentioned and increase the available dynamic range making it possible to test the full capability of the variable attenuator.

2. DIRECTIONAL COUPLER

The oversize-waveguide quasi-optical directional coupler was also tested at 330 Gc and the experimental results are shown in Figures 5 and 6. The device was operated as a single-frequency variable directional coupler and the specified 10-db coupling was readily obtainable. The curves show good agreement within the experimental error with what can be expected from a device of this type. A single measurement of directivity showed the decoupled port power level in the noise or about 10 db down from the coupled arm. This figure will be substantially improved when a coupler using matched prisms is evaluated at 330 Gc.

3. PHASE SHIFTER

A phase shifter that can provide an incremental phase shift up to 360 degrees has been completed that uses a pair of Rexolite prisms in a four-port H-plane cross. The incremental shift pertains to the relationship between the input arm and decoupled arm (as if the device were operated as a directional coupler). Micrometer-driven sliding shorts are in the two coupled arms. The prism separation is also adjustable which permits an accurate setting of 3-db coupling to operate the phase shifter properly at any chosen frequency. Figure 7 shows the completed phase shifter. To test the phase shifter, we operated it as a Michaelson interferometer at 125 and 240 Gc. The 125-Gc signal was obtained from the DX-237 klystron and the 240-Gc signal was obtained from a harmonic generator operated as a doubler. If we move one sliding short and leave the other in a fixed position, there is a periodic signal of alternating maxima and minima in the decoupled port (as in a standing wave). The distance between successive maxima or minima is $\lambda/2$ at the frequency in question. If many successive maxima are measured, an averaging will improve the determination of λ. If the device operates properly as an interferometer, it will also function properly as a phase shifter.

At 125 Gc, with unmatched prisms, the determination of the wavelength of the 125-Gc signal was accurate to two parts in a thousand. The klystron frequency was known from its calibration against control voltages. A similar result was obtained at 240 Gc. From these results, it is believed that the phase shifter will operate successfully at 330 Gc.

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C. MULTIPLE-SLAB STRUCTURES

An alternative form of directional coupler is being constructed that may have lower losses than the double-prism device (reference 1). However, we are having difficulties in obtaining proper tolerances on the ultrathin sheets of quartz (a few thousandths of an inch) and in designing the drive element for the multiple slabs. When the multiple-slab directional coupler is constructed it will be tested at 330 Gc and compared with the double-prism directional coupler. It will also be tested as a variable attenuator.

The multiple-slab coupler will consist of two sets of three quartz slabs. The nominal dielectric constant of quartz (4.1) will give this combination an attenuation range of 50 db at 330 Gc (reference 1). Thus, a 10-db coupler is easily obtainable. The drive mechanism will be similar to that of a double-prism coupler. One set of slabs will be fixed and one set will be moved by a micrometer and drive-wheel combination (Figure 8).

1. DIRECTIONAL COUPLER

Referring to the design equations derived in reference 1, the propagation constants in question are:

$$\beta_1 = \frac{2\pi}{\lambda} \ \frac{1}{\sqrt{2}} \ \text{for 45-degree incidence in air}$$

$$\beta_2 = \frac{2\pi}{\lambda} \sqrt{\epsilon_r} \sqrt{1 - \frac{1}{2\epsilon_r}} \ \text{for 45-degree incidence in quartz}$$

where the dielectric constant is 4.1.

An optimum design pertains when

$$\beta_1 d_1 = \beta_2 t = \frac{\pi}{2}$$

where t and d_1 are the slab and air thickness, respectively (reference 1). For example, at 330 Gc and a dielectric constant of 4.1, d_1 = 0.01268 inch and t = 0.00517 inch.

2. GRATING DUPLEXER

A grating duplexer not having the usual 6-db loss associated with hybrid duplexers is being constructed (Figure 9). The gratings are enclosed in oversize waveguide but will be removable for testing in free space.

Because of the difficulties in constructing the gratings with only air between the slabs, we are using quartz strips for mechanical support. The dimensions of the grating are determined in the following way.

For Grating B, the thickness ℓ of each slat must be such that there is an odd multiple of 90 degrees phase difference between the horizontal and vertical components of the wave emerging from the grating to produce the desired circular polarization. This means that

$$(\beta_v - \beta_h) \; \ell = \frac{n\pi}{2} \quad n = 1, 3, 5, \ldots$$

where

β_v = phase constant of vertical component,

β_h = phase constant of horizontal component.

Thus,

$$\beta_v = \frac{2\pi}{\lambda_o}$$

where

$$\lambda_o = \frac{30}{\sqrt{\epsilon_r} \; f} \; cm, \qquad\qquad f \; in \; Gc$$

ϵ_r = dielectric constant.

The dielectric constant of quartz at 330 Gc is unknown but we will assume it stays reasonably close to its lower frequency value (30 Gc). A radical change will affect the attenuation range obtainable. Also,

$$\beta_h = \frac{2\pi}{\lambda_o} \sqrt{1 - \left(\frac{\lambda_o}{2a}\right)^2}$$

where a is the distance between slats.

We chose n = 1 to maximize our grating bandwidth. Therefore,

$$\ell = \frac{\pi}{2(\beta_v - \beta_h)} = \frac{\lambda_o}{4\left[1 - \sqrt{1 - \left(\frac{\lambda_o}{2a}\right)^2}\right]}$$

We may also write

$$\beta_h = \frac{2\pi}{\lambda_g}$$

where $\lambda_g = \dfrac{\lambda}{\sqrt{1 - \left(\frac{\lambda_o}{2a}\right)^2}}$

so that

$$\left(\frac{2\pi}{\lambda_o} - \frac{2\pi}{\lambda_g}\right) \ell = \frac{\pi}{2}$$

A convenient ratio is $\lambda_g/\lambda_o = 1.2$. This would establish the grating dimension at practical values and also minimize higher mode propagation. With this relation,

$$2\pi\left[\frac{1}{\lambda_o} - \frac{1}{1.2\lambda_o}\right] \ell = \frac{\pi}{2}$$

or

$$\ell = 1.5 \ \lambda_o$$

Thus, λ_o = 0.455 millimeters so that ℓ = 0.0269 inch. We may now solve for a using

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$$\ell = \frac{\lambda_o}{4\left[1 - \sqrt{1 - \left(\frac{\lambda_o}{2a}\right)^2}\right]}$$

This gives us a = 0.0163 inch, which would cut off the TE_{20} mode at λ = a (or 362 Gc).

For Grating A, the dimensions are not critical but the spacing between slats is such that each pair behaves as a waveguide well below cutoff at the operating frequency for waves polarized parallel to the slats.

The gratings will be experimentally evaluated both in free space and in oversize waveguide to determine the optimum configuration. Essential characteristics such as transmission loss through the gratings, circular polarization, isolation, and insertion loss will be measured. The device is expected to perform properly in the submillimeter region on the basis of the theory and data taken at 30 Gc (reference 1).

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III. INSTRUMENTATION

Two test facilities are being used to test the oversize-waveguide components developed under this contract. These are the harmonic tripling setup at AIL and the 330-Gc carcinotron at Lincoln Laboratory. The harmonic tripling setup uses an Amperex DX-237 klystron as a 115-Gc source to feed a harmonic generator. The components are operated outside their frequency range and are used for tripling instead of doubling to provide an output in the submillimeter range. Bolometers are used as detectors. We have been unable (as yet) to obtain useful measurements above 240 Gc with this setup.

The measurements above 330 Gc were made with a carcinotron at Lincoln Laboratory (as described in Section II). The system was set up so that the power supply was incapable of modulation, therefore modulation had to be done with a ferrite RF modulator, which caused considerable problems. These problems will be minimized if further tests are made at Lincoln Laboratory.

The harmonic generator described in reference 1 has been constructed but initial evaluation of the system was delayed by inoperative bolometers that had to be returned to the manufacturer. The Philips harmonic generator used initially appears to need frequent whisker changing and is difficult to adjust. The FXR generator is more stable and has a fixed whisker semiconductor contact.

Our straight-video detection scheme using bolometers has been unable to detect third harmonic power (360 Gc). Since the best measurement of second harmonic power (240 Gc) shows a 24-db signal-to-noise ratio, and a 30-db loss from second to third harmonic is not unlikely, we are investigating improved methods of detection such as a harmonic superheterodyne receiver (reference 3). If this is not fruitful, the 330-Gc carcinotron will be used exclusively. The dynamic range of the carcinotron should provide an adequate test of all the components developed under the contract.

IV. CONCLUSIONS

Various components have been developed using over-size-waveguide quasi-optical techniques and successfully tested in the submillimeter range. Other components have been tested at 125 and 240 Gc and these are awaiting testing at the higher frequencies. However, these latter components operate properly at 125 and 240 Gc and should perform satisfactorily above 300 Gc.

The development of a grating duplexer is nearly complete and it will be tested at 330 Gc since its design is such that it cannot be used at 125 or 240 Gc.

Work on the instrumentation for tripling (to 360 Gc) is continuing. Successful doubling from 120 to 240 Gc has already been achieved. However, the CSF carcinotron (330 Gc) will continue to be used as a direct source until the harmonic tripling setup can provide sufficient range for testing.

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V.   PROGRAM FOR NEXT QUARTER

The work under this program will be completed during the next quarter. The optimum form for each component will then have been determined and the device built. All components (directional coupler, variable attenuator, phase shifter, and duplexer) will be tested in the submillimeter region and will be checked against specifications. No difficulty is expected in this respect and all specifications should be met.

VI. REFERENCES

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2. J. M. Cotton and M. Cohn, "Millimeter Wave Research," RADC-TDR-62-287, 31 May 1962.

3. C. M. Johnson, "A Superheterodyne Receiver for the 100 to 150 kmc Region," IRE Transactions (PGMTT), Vol II, No. 3, September 1954.
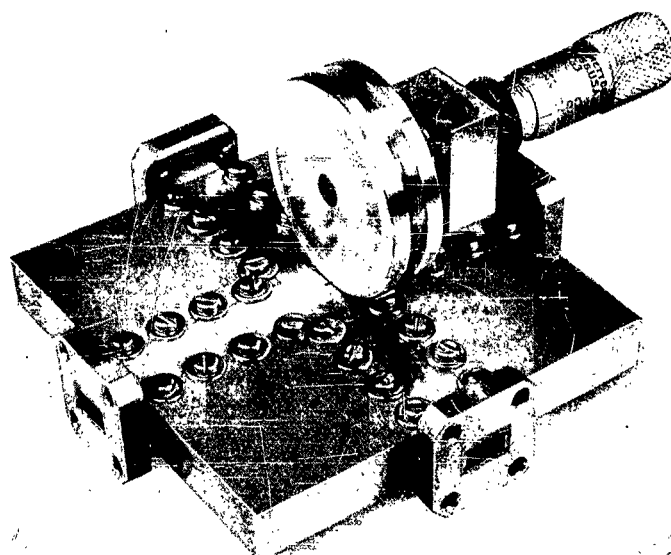
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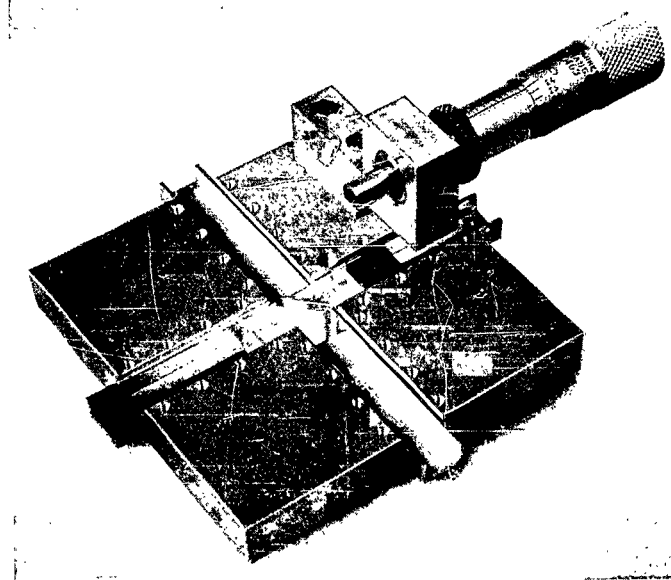
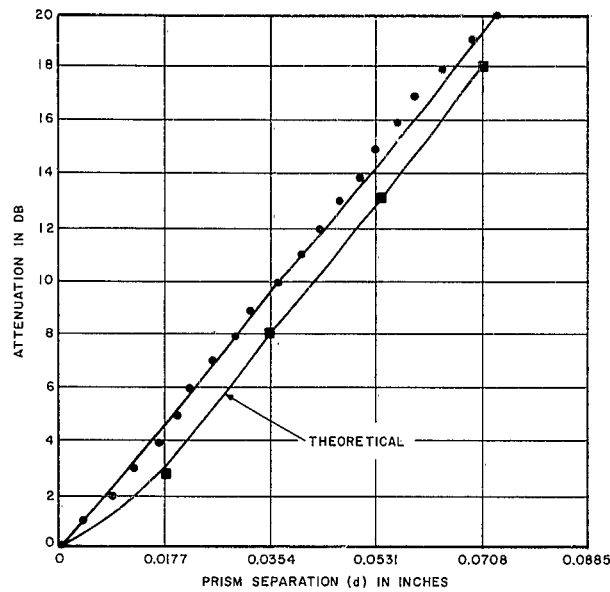B. DISASSEMBLED

FIGURE 1.   VARIABLE ATTENUATOR

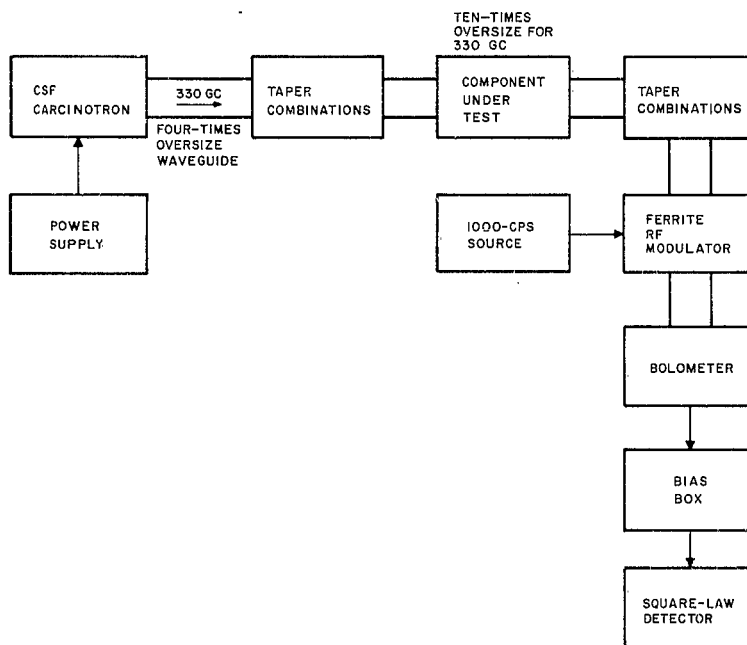FIGURE 2. ATTENUATION VS PRISM SEPARATION (125 GC)
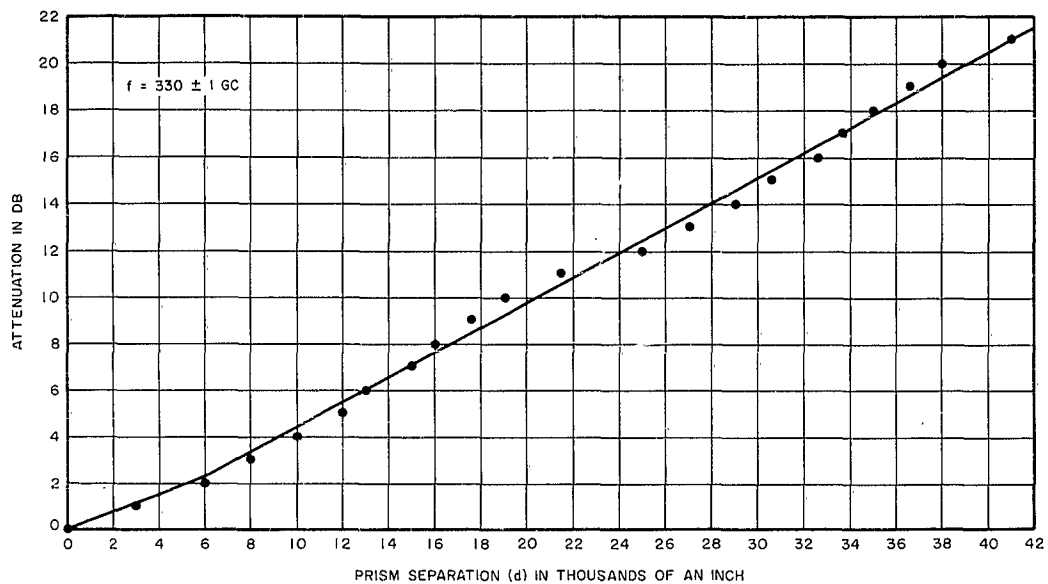

FIGURE 3. BLOCK DIAGRAM OF MEASUREMENT SETUP AT 330 GC

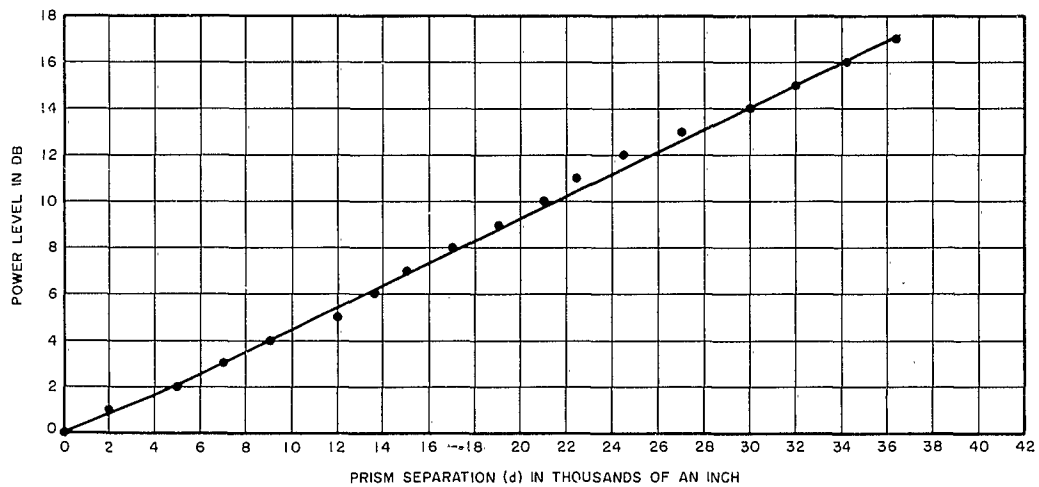FIGURE 4.   ATTENUATION VS PRISM SEPARATION (330 GC)

FIGURE 5.   POWER LEVEL VS PRISM SEPARATION (POWER IN STRAIGHT-
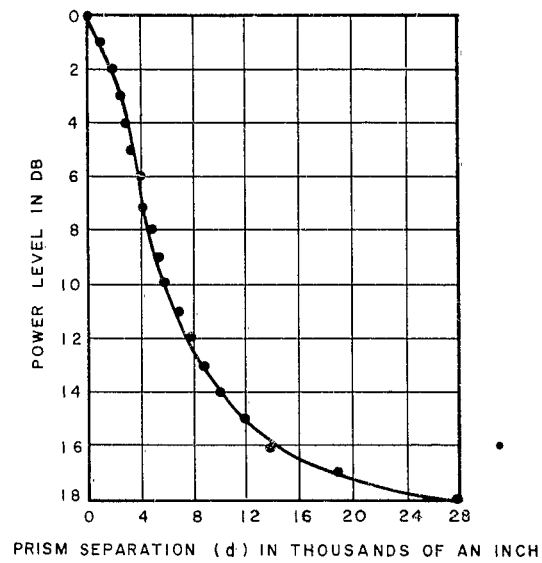   THROUGH ARM) FOR DIRECTIONAL COUPLER AT 330 GC

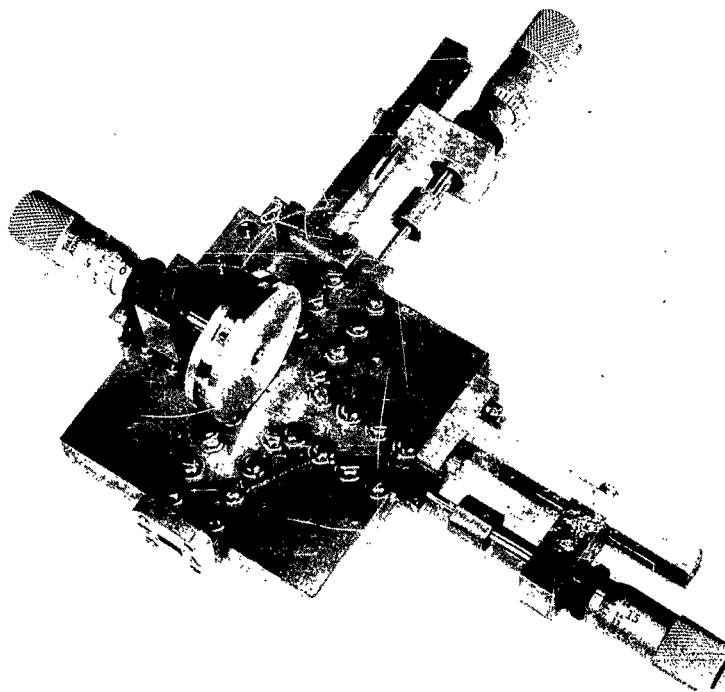FIGURE 6. POWER LEVEL VS PRISM SEPARATION (POWER IN PERPENDICULAR ARM) FOR DIRECTIONAL COUPLER AT 330 GC

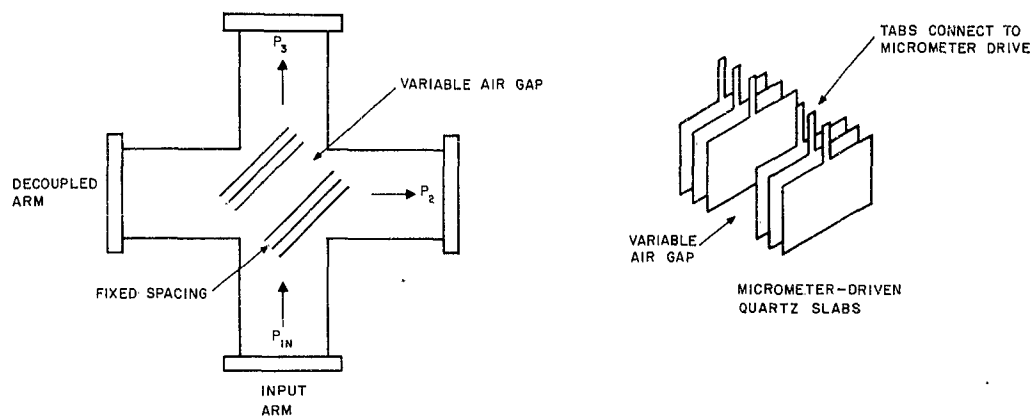FIGURE 7. COMPLETED PHASE SHIFTER
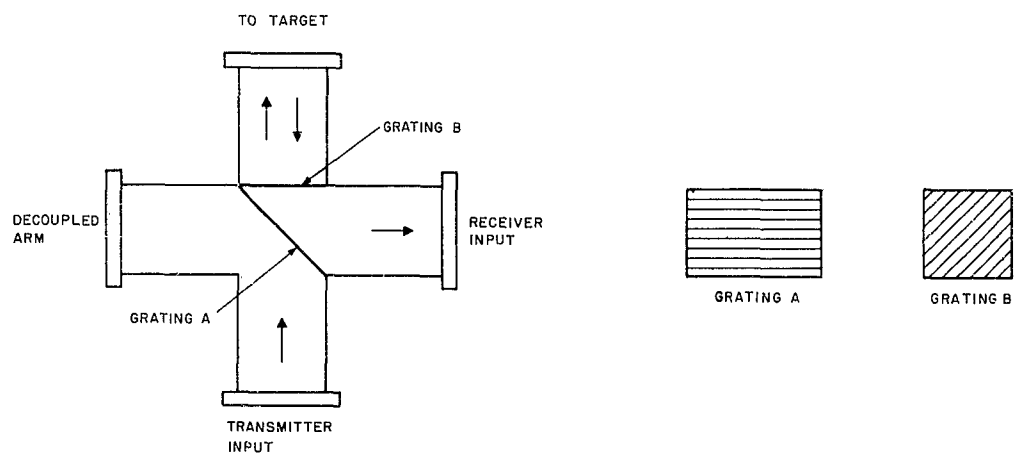
FIGURE 8.   MULTIPLE-SLAB COUPLER

FIGURE 9.   GRATING DUPLEXER

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